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CHECKING AND ANALYZING SOIL TEMPERATURE MEASUREMENTS

PART I: TESTING RESULTS WITH THE AID OF TAUTOCHRONE PLOTS

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CHECKING AND ANALYZING SOIL TEMPERATURE MEASUREMENTS

PART I: TESTING RESULTS WITH THE AID OF TAUTOCHRONE PLOTS

by

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In order to maintain the reliability of observations or recordings of soil temperature it is necessary not only to follow general instructions when installing the thermometers but also to check the current results. For this purpose it is most suitable to plot the data in the form of tautochrones. As an example, the monthly tautochrones for one year of observations at Vienna-Hohe Warte are given.

A network of soil-temperature measuring stations should operate with instrumentation which is as uniform as possible, under uniform guidelines for installation, etc., to make the results accessible for simple checking and direct comparison. The Central Laboratory for Meteorology and Geodynamics has compiled a concise guide for its observation stations (cf. the section entitled "For practical application") and has provided instructions for checking the measurement system. As experience has shown, however, additional checks are indispensable for obtaining really usable measurement results.

At present it appears necessary to use only truly first-class, calibrated thermometers. Shortcomings such as unaged glass, impure mercury, alcohol as the filler liquid, red scale markings, paper scales, etc., only become noticeable within a prolonged period of measurement (one-half year) and can usually no longer be remedied at that time. Calibration of the thermometer itself is also no longer likely to be repeated, since recalibration always results in alteration of the borehole and ground contact, and often breakage of the thermometer. It is also necessary to place the thermometer at the intended depth with the greatest possible care. If the thermometer bulbs are vertical cylinders, the midpoints of the cylinders must be placed at the indicated depth; if they are horizontal cylinders -- something which must be sought at depths above 10 cm -- the axes of the cylinders determine the depth. Soil-temperature records also can contain errors (inexact soil depths, errors in level and amplitude readings).

The many causes for systematic errors in soil-temperature observations can ultimately be revealed only in a check of the observation results. A prerequisite for the successful application of this check is an adequately large number of soil depths which are covered. Measurements should be taken at least at all internationally recommended depths (10, 20, 50 and 100 cm), if additional depths are not of interest for special agricultural purposes (2, 5 and 30 cm). Results obtained from fewer than three depths cannot be checked.

For checking, it is best to use the curve of soil temperature versus depth at each of the three observation times. Due to constantly changing weather conditions and their delayed effect upon soil temperature, individual measurements are not well suited to making checks; average values over a calendar month or a period of time with uniform weather conditions will therefore yield better results. Daily averages should not be used even for checking purposes, however, since these do not represent real temperature conditions in the soil, and their curves with respect to depth are not very characteristic.

The method consists of plotting average values of soil temperature in the form of tautochrones for every month and for at least two reading times (7 AM and 2 PM) and estimating the correctness of the measured curves with the aid of similar curves from a standard station. By interpolation of the intermediate depths or extrapolation of the boundary values, we are then able to correct the results or -- if they deviate too much -- have the erroneous results remedied (correction of depth, replacement of thermometer).

The shape of the tautochrone can be easily interpreted physically, since it provides very clear information on the heating processes taking place at the soil depth under consideration. The most important elements of the tautochrone form can be taken from Fig. 1.

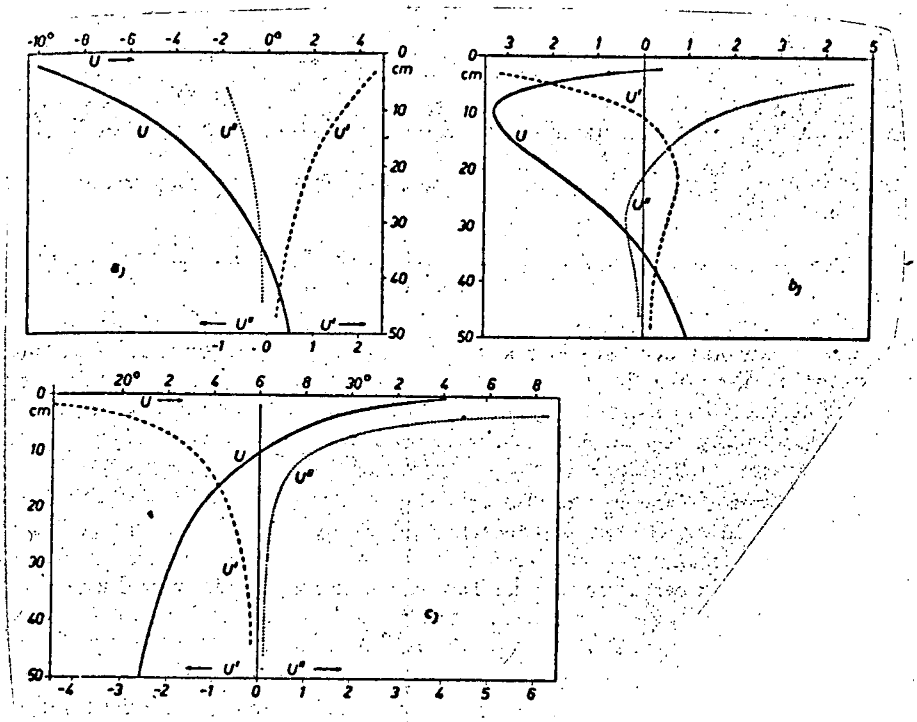

Fig. 1. Curves of temperature u, its first derivative (du/dz) and second derivative (d^2u/dz^2) with respect to depth z.
a) February 8, 1960, 7 AM. Vienna - Hohe Warte, bare, snow-free ground. Scale unit for u, 2°C; for du/dz, 0.5°/cm; for d^2u/dz^2, 0.062°/cm^2.
b) February 8, 1960, 2 PM. Vienna - Hohe Warte, bare, snow-free ground, intense solar radiation. Scale unit for u, 1°C; for du/dz, 0.25°/cm; for d^2u/dz^2, 0.031°/cm^2. Abscissa: left, negative; right, positive.
c) July 28, 1959, 2 PM. Vienna - Hohe Warte, grass-covered ground, intense solar radiation. Scale units as for b).

Assuming a coefficient of thermal conductivity λ of 0.002 cal/cm·sec·degree and a temperature conductivity coefficient K of 0.005 cm^2/sec, we obtain the following values for hourly heat transport q and hourly temperature change τ per scale unit:

[Fig. 1 continued]

	$q(\mathrm{cal/cm^2 \cdot h})$	$\tau(^\circ C)$
a) February 8, 1960, 7 AM	1.8	0.56
b) February 8, 1960, 2 PM	3.6	1.12
c) July 18, 1959, 2 PM	3.6	1.12

The simplest form is a line. Its slope corresponds to a constant temperature rise or drop in the soil. In this case, assuming constant heat-conduction conditions, a constant heat flow will pass upward or downward through the soil without the soil temperature's changing with time, since $q = -\lambda \cdot du/dz$. If a tautochrone is made up of curved segments ($d^2u/dx^2 \gtrless 0$), this indicates a heat flow which varies with depth, which causes zones of heat accumulation or heat removel. Since $du/dt = K \cdot d^2u/dz^2$, a change in temperature with time occurs at these points.

Three different tautochrones are shown in Fig. 1, one with a curvature which is concave to the left (January [sic] 8, 1960, 7 AM, under bare ground), one with curvature concave to the right (July 28, 1959, 2 PM, under grass), and one with a double curvature (January [sic] 8, 1960, 2 PM). Not only $u(z)$ but also du/dz and d^2u/dz^2 are plotted for each of these tautochrones. We see that the vertical temperature gradient du/dz and the opposing heat flow $q = -\lambda \cdot du/dz$ depend upon the slope of the tautochrone relative to the z-axis (more precisely, upon the tangent of the slope angle) and increase proportionally to it.

The timewise temperature gradient $du/dt = K \cdot d^2u/dz^2$ is a function of the direction and magnitude of curvature, such that the temperature change takes place on the side of concave tautochrone curvature and is proportional to it. Heating from the direction of the surface always results in a temperature drop with depth and a curve which is concave toward the right. Cooling from the direction of the surface, on the other hand, is indicated by an increase in temperature with depth and a curvature concave to the left.

A tautochrone with a double curvature accordingly indicates two zones with heat flows in different directions, and two zones with timewise temperature changes of different sign. The heat flow changes its direction at the depth at which temperature passes through an extreme; the timewise change in temperature changes sign where the vertical temperature gradient passes through an extreme.

For each depth, it also holds that the temperature extreme occurs one-eighth of a day (or year) later than that of the vertical temperature gradient; this in turn reaches its extremes one-eighth day (or year) later than the timewise temperature gradient. Thus the most pronounced timewise temperature changes are reached three hours (one and one-half month) before the maximum vertical temperature gradient and six hours (three months) before the extreme in temperature itself. This behavior derived from theory can only be checked by means of recorded values with respect to diurnal variation. The relationship between temperature extremes and maximum timewise temperature change is well satisfied in the yearly variation in soil temperature, both for the maximum and for the minimum. With regard to diurnal variation, however, it is satisfied only approximately for the temperature maximum during the warmer half of the year.

The monthly tautochrones of daily averages exhibit an approximately constant slope across the overall depth, the sign and magnitude of which depends upon the season. From April to August, it is negative, corresponding to a decrease in temperature with depth; from October to February it is positive, and is almost zero during the transition months of March and September (April and August at high elevations). The periodic daily temperature gradient is superimposed on this seasonal gradient, as shown in Fig. 2 for one summer month. The 9 PM tautochrone is concave toward the left and indicates an increasing upward heat flow in the upper 10-cm layer, which results in cooling. The 2 PM tautochrone, with a decreasing heat flow downward, is associated with heating to a depth of about 30 cm. The 7 AM tautochrone, with a curvature concave to the left down to about 30 cm, again corresponds to an upward flow of heat, but this reverses in the uppermost 5 cm.

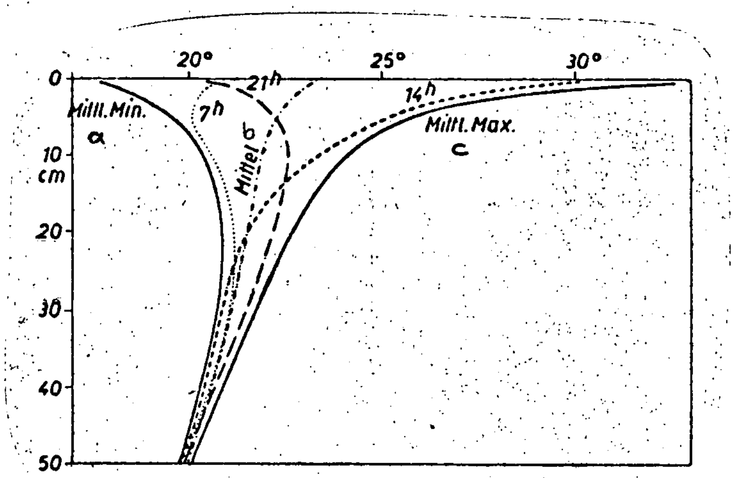

Fig. 2. Average tautochrones from values recorded at Vienna - Hohe Warte in July, 1957, under grass-covered ground. 7 AM, 2 PM, 9 PM, daily average, extremes.

Key: a. average minimum
b. average
c. average maximum
21^h, 14^h = 9 PM, 2 PM

Fig. 3 shows the average tautochrones of soil temperatures recorded at Vienna - Hohe Warte under grass for all three times during each month of the year 1957. Although the basic character of the shape remains the same in each month, clear differences are exhibited by the seasons. As already mentioned, a decrease in temperature with depth occurs beyond 20 cm from March to July and an increase from September to December. In the uppermost 20 cm,

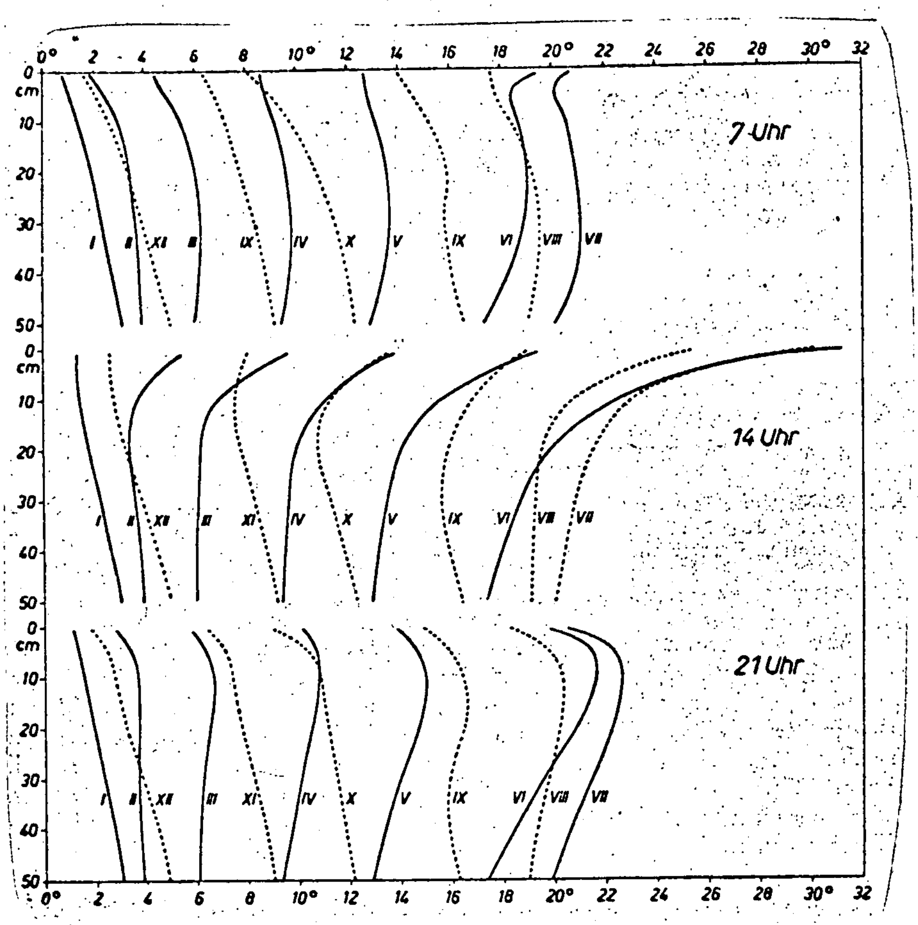

Fig. 3. Average tautochrone shapes for all months at 7 AM, 2 PM and 9 PM. From records taken at Vienna - Hohe Warte under grass-covered ground, 1957.

Key: Uhr = o'clock [24-hour system]; I.-XII. = Jan.-Dec.

however, the effect of the daily periods prevails, determined in turn by the seasonally changing length and intensity of global radiation. At 9 PM, the temperature drop toward the surface caused by heat dissipation can already be detected to a depth of 10 cm; by 7 AM, this drop is more pronounced and reaches down to 30 cm. A peculiarity is observed in the first 5 cm from April to August at this hour, however: the pronounced temperature drop caused by nightly heat dissipation from the surface is slowed down; in the months of June and July, it is actually reversed into a temperature rise since the sun, which has already been above the horizon for several hours, has already heated the surface.

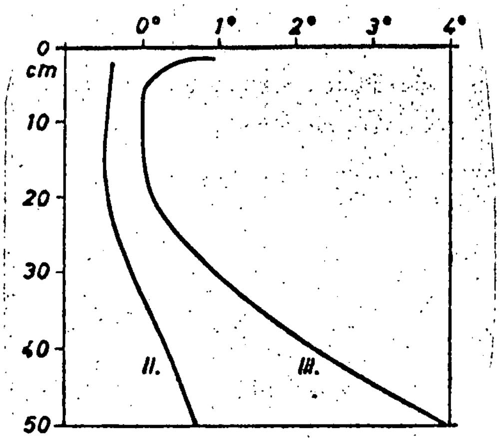

Fig. 4. Tautochrones for snow-covered and frozen ground in February and March. Mean monthly temperature maxima at Rinn, Tirol.

The tautochrones shown in Fig. 3 naturally experience changes in shape as a function of weather conditions and surface and soil characteristics. Dryness causes temperature extremes. Both midday heating and nightly cooling, and therefore the curvature of tautochrones, become more pronounced. Relatively high soil moisture (due to infiltrating precipitation or ground water) reduces the formation of temperature extremes, due to the improved conductivity; the tautochrones remain straighter. Thick snow suppresses all periodic diurnal temperature change during the winter.

If the ground becomes frozen, an unusual tautochrone shape is observed in late winter, with a straight, vertical segment (Fig. 4). Heat entering both from above and from below can produce no temperature rise until the ground ice has melted away, while the average temperature rise from February to March at a depth of 50 cm is as much as 3.4°.